MIXTURE-FRACTION AND VELOCITY STATISTICS IN FULLY-DEVELOPED PLUMES

by

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Introduction. An experimental investigation of mean and fluctuating mixture fractions and velocities within fully-developed round turbulent plumes is described. This problem is of interest as a classical buoyant turbulent flow that is relevant to flows found in fire environments. Conditions within the fully-developed, or self-preserving, portions of the flow were emphasized, where both mean and turbulent properties exhibit similarity when variables are scaled appropriately. Such conditions are helpful because interpretation of the measurements is simplified, and use of the results to develop models of buoyant turbulent flows is facilitated because effects of extraneous source disturbances have been lost.

Round turbulent plumes have attracted significant attention since the classical study of Rouse et al. [1] who identified the scaling relationships for self-preserving conditions. Subsequently, many workers reported observations of mean and fluctuating properties within self-preserving plumes, however, there were considerable differences among the various determinations of centerline values and flow widths [1-15]. Reasons proposed for these difficulties include both conventional experimental uncertainties and problems of reaching self-preserving conditions [11,12]. Whether self-preserving conditions were reached is particularly questionable. While existing results generally reached conditions where buoyancy properly dominates effects of source momentum, according to Morton's [16] criterion, the measurements involve relatively small streamwise distances from the source, $(x-x_o)/d$ in the range 6-62 where $(x-x_o)$ is streamwise distance from the virtual origin and d is source diameter, in comparison to values required for self-preserving conditions in nonbuoyant jets [17,18]. Thus, the objectives of the present study were to complete measurements of mixture fraction and velocity properties at greater distances from the source, up to $(x-x_o)/d = 151$, in order to gain a better understanding of properties within self-preserving plumes and requirements for the onset of this flow regime. The following discussion is brief, additional details can be found in Dai et al. [19].

Experimental Methods. Plume conditions were simulated using round dense gas sources (carbon dioxide and sulfur hexafluoride) in still air. A screened enclosure was used to control room disturbances. Scalar properties were represented by the mixture fraction (the mass fraction of source gas in a sample), using state relationships for isothermal mixing to find other scalar properties. Mixture fractions were measured by seeding the source flow with iodine vapor and using two-point laser-induced iodine fluorescence (LIF). The two-point LIF configuration allowed direct measurements of radial spatial correlations. Mean and fluctuating velocities were measured using a dual-beam, frequency-shifted laser velocimeter (LV) with the flow seeded with drops having nominal diameters less than 1 μm.

Results and Discussion. Figures 1 and 2 illustrate the evolution of mean and fluctuating mixture fractions. $\bar{f}$ and $\bar{f}'$, with streamwise distance, where Fr_o is the source Froude number, ρ_o and ρ_∞ are the source and ambient densities, r is radial distance and the subscript c denotes conditions at the flow axis. The variables in these figures are scaled according to the requirements of self-preserving round turbulent plumes [16-18]. The results show a progressive narrowing of the flow with increasing distance until self-preserving conditions are reached for $(x-x_o)/d \geq 87$. This region is more than 12 Morton length scales from the source so that effects of buoyancy are dominant [16,18], with plume Reynolds numbers of 2500-4200 which are reasonably high for unconfined turbulent flows [18-20]. The present self-preserving plumes are narrower, with larger scaled values at the axis, than past results [1-15] which appear to be in the transitional portion of the flow.

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Effects of buoyancy on the properties of turbulent plumes can be seen from the plots of $\bar{f}'$ in Fig. 2. In particular, results near the source exhibit a dip near the axis, similar to nonbuoyant jets [17,18]. The dip disappears in the self-preserving region, however, yielding values of maximum mixture fraction fluctuations roughly twice those observed in nonbuoyant jets. This behavior can be attributed to turbulence production near the axis of plumes due to buoyant instability in the streamwise direction. Another interesting effect of buoyancy/turbulence interactions in plumes is that the conventional -5/3 power decay of the temporal power spectra, associated with the inertial subrange of turbulence, is followed by a prominent -3 power subrange that is not seen in nonbuoyant turbulence. This latter region is called the inertial-diffusive subrange where the local dissipation of turbulence kinetic energy is caused by buoyancy-generated inertial forces rather than viscous forces [12].

Figures 3 and 4 are illustrations of mean and fluctuating streamwise velocities, $\bar{u}$ and $\bar{u}'$, within the self-preserving region, where u_o is the mean source exit velocity. The variables in these figures also are scaled according to the requirements of self-preserving round turbulent plumes [16-18]. The present measurements of mean velocities also yield narrower profiles with larger scaled values near the axis than earlier results for transitional plumes in the literature [1-15] similar to the profiles of mean mixture fractions.

Effects of buoyancy are less evident for streamwise velocity fluctuations, Fig. 4, than for mixture fraction fluctuations, Fig. 2. In particular, the presence of the dip near the axis for velocity fluctuations is similar to the behavior of nonbuoyant jets [17,18]. In fact, turbulence intensities near the axis are slightly lower for self-preserving plumes, 0.22, than for nonbuoyant jets, 0.25, see [12]. Thus, buoyancy/turbulence interactions simultaneously act to reduce velocity fluctuation intensities, and increase mixture fraction fluctuation intensities, near the axis of self-preserving turbulent plumes in comparison to turbulent nonbuoyant jets. Another effect of buoyancy/turbulence interactions is that a prominent inertial-diffusive region, with a -3 power decay with increasing frequency, is seen in the temporal power spectra of streamwise velocity fluctuations of self-preserving turbulent plumes that is not seen in nonbuoyant jets—analogous to behavior discussed earlier for mixture fraction fluctuations.

Modeling Implications. The differences between past and present estimates of self-preserving turbulent plume properties can have a considerable impact on the development and evaluation of models of turbulence. In particular, Pivovarov et al. [21] tested a variety of contemporary turbulence models based on predictions assuming self-preserving flow in plumes and compared these predictions with the measurements of Refs. [3,4,7,8,15]—all of which involve transitional plumes based on present findings. Based on these results, Pivovarov et al. [21] recommended substantial changes of turbulence model constants established from past work in nonbuoyant flows. Nevertheless, their predictions using conventional turbulence model constants are in reasonable agreement with present measurements that more accurately reflect conditions within self-preserving turbulent plumes.

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References.

1. H. Rouse, C.S. Yih and H.W. Humphreys, Tellus 4:201-210 (1952).

2. G. Abraham, ASCE J. Hyd. Div. 86:1-13. (1960).

3. W.K. George, Jr., R.L. Alpert and F. Tamanini, Int. J. Heat Mass Trans. 20:1145-1154 (1977).

4. H. Nakagome and M. Hirata, in *Heat Transfer and Turbulent Buoyant Convection* (D.B. Spalding and N. Afgan, eds.), McGraw-Hill, New York, 1977, p. 367.

5. R.A. Seban and M.M. Behnia, Int. J. Heat Mass Trans. 19:1197-1204 (1976).

6. V.D. Zimin and P.G. Frik, Izv. Akad. Nauk. SSSR, Mekh. Zhid. Gaza 2:199-203 (1977).

7. T. Mizushima, F. Ogino, H. Veda and S. Komori, Proc. Roy. Soc. London A366:63-79 (1979).

8. F. Ogino, H. Takeuchi, I. Kudo and T. Mizushima, Int. J. Heat Mass Trans. 23:1581-1588 (1980).

9. N.E. Kotsovinos and E.J. List, J. Fluid Mech. 81:25-44 (1977).

10. N.E. Kotsovinos, Int. J. Heat Mass Trans. 28:771-777 (1985).

11. P.N. Papanicolaou and E.J. List, Int. J. Heat Mass Trans. 30:2059-2071 (1987).

12. P.N. Papanicolaou and E.J. List, J. Fluid Mech. 195:341-391 (1988).

13. D. Papantoniou and E.J. List, J. Fluid Mech. 209:151-190 (1989).

14. J. Peterson and Y. Bayazitoglu, J. Heat Trans. 114:135-142 (1992).

15. A. Shabbir and W.K. George, NASA Technical Memorandum 105955, 1992.

16. B.R. Morton, J. Fluid Mech. 5:151-163 (1959).

17. J.O. Hinze, *Turbulence*, 2nd ed., McGraw-Hill, New York, 1975, p. 175.

18. H. Tennekes and J.L. Lumley, *A First Course in Turbulence*, M.I.T. Press, Cambridge, 1972.

19. Z. Dai, L.-K. Tseng and G.M. Faeth, J. Heat Trans., in press.

20. J.-S. Wu and G.M. Faeth, AIAA J., in press.

21. M.A. Pivovarov, H. Zhang, D.E. Ramaker, P.A. Tatem and F.W. Williams, Combust. Flame 92:308-319 (1992).

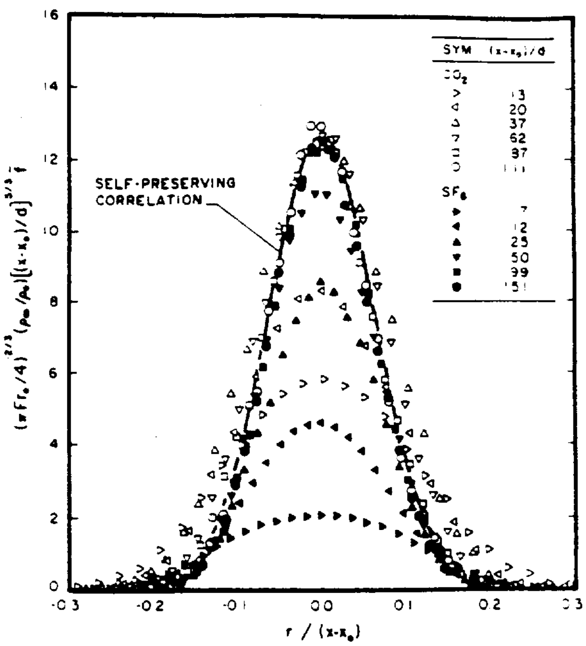

Fig. 1 Radial profiles of mean mixture fractions.

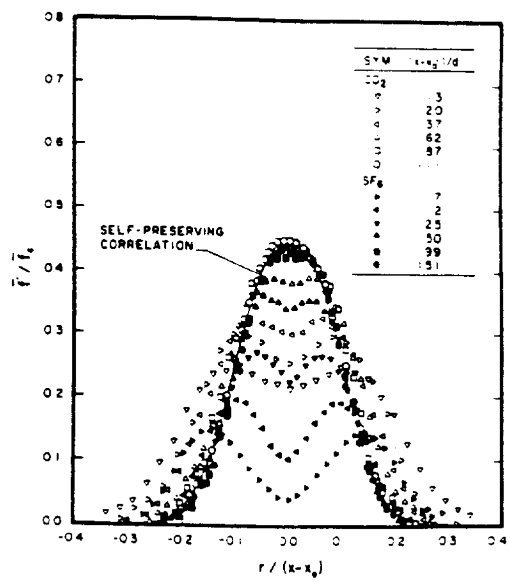

Fig. 2 Radial profiles of mixture fraction fluctuations.

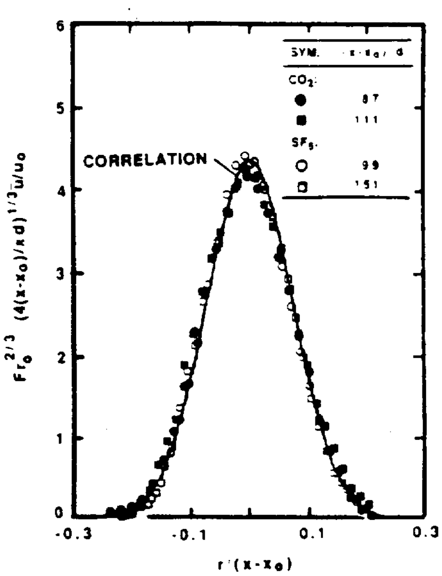

Fig. 3 Radial profiles of mean streamwise velocities.

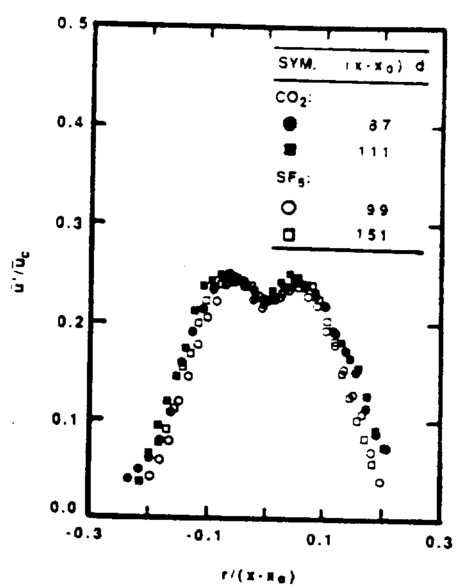

Fig. 4 Radial profiles of streamwise velocity fluctuations.